STUDY FOR MITIGATING SCOUR AROUND THE MONOPILE FOUNDATIONS OF OFFSHORE WIND TURBINES

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Abstract

Scour occurring around the monopile foundations of offshore wind turbines has been widely reported in recent years. It threatens the safety and reliability of those offshore wind turbines supported by monopile foundations. Currently, tons of rock/stone are poured down around the foundations as a measure for mitigating scour. However, such a method is costly and inconvenient to implement at offshore site. Moreover, the rock and stone will spread on the seabed over time. It will be very difficult to recycle them in the future. Therefore, it has become a pressing task to address this issue particularly in the light of fact that the offshore wind industry is booming across the world today and more and more wind turbines will be installed offshore and supported by monopile foundations. Motivated by this urgent requirement, the feasibility study of a new scour reduction technique, namely fishnet, is conducted in this paper by the approach of numerical analysis. From the numerical research, it is found that in contrast to existing scour mitigation method, fishnet is not only effective in reducing scour around the wind turbine monopile foundations, but is also more cost-effective and easier to deploy at site.

1 Introduction

The offshore wind industry is rapidly growing worldwide. It is predicted that the global installed capacity of offshore wind will reach 46.4 GW by the end of 2022, of which 33.9 GW will be installed in Europe, 11.3 GW in Asia and 1.2 GW in North America [1]. In order to avoid the risks in operation and thereby reduce the cost of wind project, at present most existing offshore wind turbines are installed in nearshore shallow water, where the mature monopile foundation technology can be readily applied [2]. However, the application of monopile foundations also shows limitations in practice. For example, they are not applicable to deep water and their installation cost will increase exponentially with increasing water depth; they are very difficult to be fully decommissioned in the future, etc. [3]. Among these limitations, one of the most markable issues is the scour happening around the monopile foundations of offshore wind turbines. According to [4], the problem of scour around offshore wind foundations was first found at the Egmond aan Zee wind farm in the Netherlands. Dong Energy reported that the similar problem was also found later on in their offshore wind farms at Burbo Bank and Gunfleet Sands. Renewables UK predicted that it could cost £5 million to fix the 336 offshore turbines in the UK that were through to be at risk at that time [4, 5]. Scouring is a phenomenon that is observed when water flow passes a monopile structure installed on seabed. In the process of scour, the turbulent water flow will stir sand particles on the seabed, pick them up, and transport them away from the monopile structure. Consequently, holes will appear around the monopile sooner or later depending on flow speed. There is no doubt that these holes will threaten the reliability of the monopile foundations of offshore turbines. They should be detected and fixed as early as possible. In fact, before this the similar phenomenon has long been observed from bridge piers. Moreover, much effort has been spent to overcome the scour issues in the area [6-10]. The achieved techniques can be roughly classified into two categories. The techniques in the first category are through bed-armouring, and the techniques in the second category are via flow-altering. In the first category, hard engineering materials, such as block, rack riprap, gravel bags, matrasses, and tetra pods, are placed on the seabed surrounding the pier to prevent excessive scouring. In the second category, additional devices, such as sacrificial piles, delta-wing-like fins, and submerged vanes in front of the piers, collars on the piers, slots through the piers, and surface guide panels, are employed to alter the flow around the bridge piers to avoid the direct scouring of riverbed. A comprehensive review of these techniques can be found from [11, 12]. However, these techniques show various limitations in practical applications. For example, the slot may be blocked in application and lose effectiveness sometimes; sacrificial piles are effective only in clear water. They are less effective under live-bed condition due to the passage of bed forms; the stability of surface guide panels will be challenged by the floods, and so on.

Inspired by the idea of using riprap to reduce the scour at bridge piers, currently the scour protection of offshore wind turbine monopile foundations are realised mainly through pouring tons of stones and rocks down to the seabed around the turbine foundations. This is a costly measure as it needs to employ large vessels to carry and transport stones and rocks. Besides this, to recycle these stones and rocks in the future decommission will be very difficult as well. Therefore, to date how to reduce the scour around offshore wind turbine monopile is still an open question remaining to resolve. This motivates the research of a radical new scour reduction technique in this paper. It is named as ‘Fishnet’.

2. Hypothesis of 'Fishnet' technique

As shown in Fig.1, scour digs holes around offshore wind turbine monopile foundation mainly via the down flow that is formed in front of the monopile foundation, the horseshoe vortices formed on both sides of the monopile foundation, and the vortices formed behind the monopile foundation.

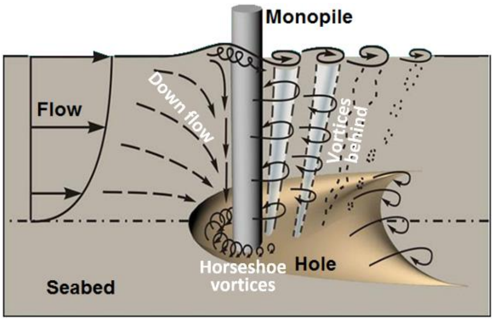


Fig.1 Reasons of scour around a monopile foundation

From Fig.1, it is easily known that if the speed of the down flow in front of the monopile and the intensities of the side- and behind-vortices can be reduced, then the scour can be reduced as a consequence. In order to develop an effective method to reduce the speed of down flow and the vortices around the wind turbine monopile foundation, here passive flow control techniques are studied first. It is known that in the Oil & Gas industry, some passive flow control techniques have been developed, as shown in Fig.2, in order to suppress the vortex induced vibration of cylinder structures so as the damage by fatigue can be avoided [11].

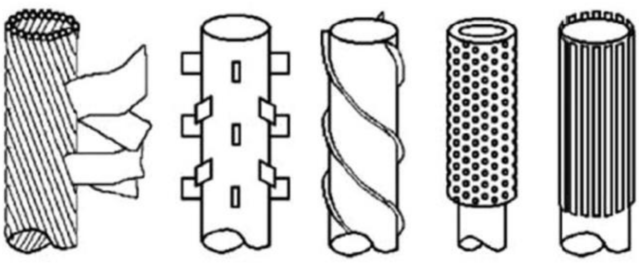


Fig.2 Helical strakes for controlling vortex induced vibration

These helical strakes work by breaking up the coherence of vortex shedding along the surface of the cylinder structure, thereby reducing the cyclic transverse forces acting on the structure. Briefly speaking, the application of these helical strakes can successfully control the vortices behind cylinder structures. Since the scour is mainly driven by vortices, in theory, theyshould work as well in reducing the down flow speed and the vortices if they are attached on surface of the wind turbine monopile foundation. However, from Fig.2 it is seen that the structures of these helical strakes are very complex and very difficult to make in real life. In the Oil & Gas industry, they are welded on the steel structures. Obviously, that is a time consuming and costly job. In particular, it is very difficult and challenging to conduct welding job in marine environment. For these reasons, they are not ideal to be applied to protect those existing offshore wind turbines that are in operation. The 'Fishnet' technique, which is originated from the aforementioned helical strakes, is timely proposed in this paper just in order to address this issue. It is illustrated in Fig.3.

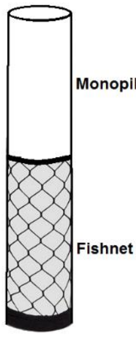


Fig.3 Schematic diagram of Fishnet technique

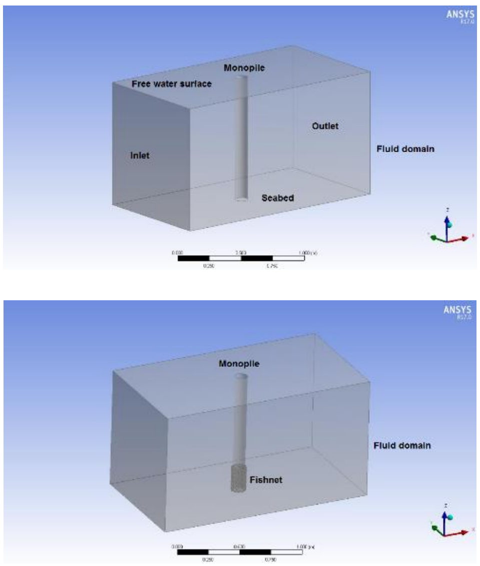
As shown in Fig.3, in the proposed technique an artificial structure looks like usual fishnet will be attached on the surface of the bottom section of the wind turbine monopile foundation. The diamond nets will change the local surface roughness of the monopile and disturb the path of local flow. There is no doubt that the speed of down flow will be reduced on the rough surface. From the point of view of fluid dynamics, the flow is more difficult to separate from a rough surface than from a smooth surface. So, the nets will, to certain extent, prevent the occurrence of shedding. This is beneficial to control the vortices. In the meantime, as nets disturb the path of local flow, turbulent flow will be generated locally, which will consume somewhat the energy of the vortices around the monopile foundation and thus reduce their intensities. Therefore, in theory, the proposed 'Fishnet' technique should work in reducing scour. In contrast to existing helical strakes techniques shown in Fig.2, 'Fishnet' technique also shows advantages in other aspects. For example, the fishnet is made of plastics or other composite materials, which are free of corrosion issue in marine environment; it is light in weight and therefore easy to install, replace and repair at site; it is easy to obtain from commercial market, therefore cost-effective, and so on. From these points of views, the proposed 'Fishnet' technique should be a potentially viable technique for addressing the sour issue that is encountered in the offshore wind industry. Hence, in order to investigate its potential in scour reduction, a feasibility study is conducted in this paper and the details of the research are reported in the following.

3. Numerical models of 'Fishnet' technique

In order to investigate the potential of 'Fishnet' technique in scour reduction, a feasibility study of its effectiveness on scour reduction is conducted in this section by the approach of numerical analysis. In this feasibility study, a 1/50 scale model of a 5 MW offshore wind turbine was considered. In the numerical calculation, it is assumed that the flow speed u satisfies the following profile [5]:

$$u(z) = \begin{cases} \left(\frac{z}{0.32h}\right)^{\frac{1}{7}} \bar{u} & 0 < z < 0.5h \\ 1.07\bar{u} & 0.5h < z < h \end{cases} \qquad (1)$$

where z refers to the distance above seabed, h indicates water depth, and $\bar{u}$ is the depth average flow speed.
Then the flow speed profile is used to define the input flow based on the assumption that the flow speed is 0.7 m/s at the distance of $0.32h$ above seabed.
Subsequently, a numerical model is developed in ANSYS FLUENT to simulate the monopile foundation of an offshore wind turbine, as shown in Fig.4. Where, the monopile foundation is assumed installed in 1 m depth water and its diameter is 0.1 m. The monopile foundation is placed in the middle of the fluid domain. The fluid domain is 220 m long, 60 m wide, and 30 m high. Such a fluid domain provides a large wake region, which can guarantee the accuracy of numerical calculation.



(a)

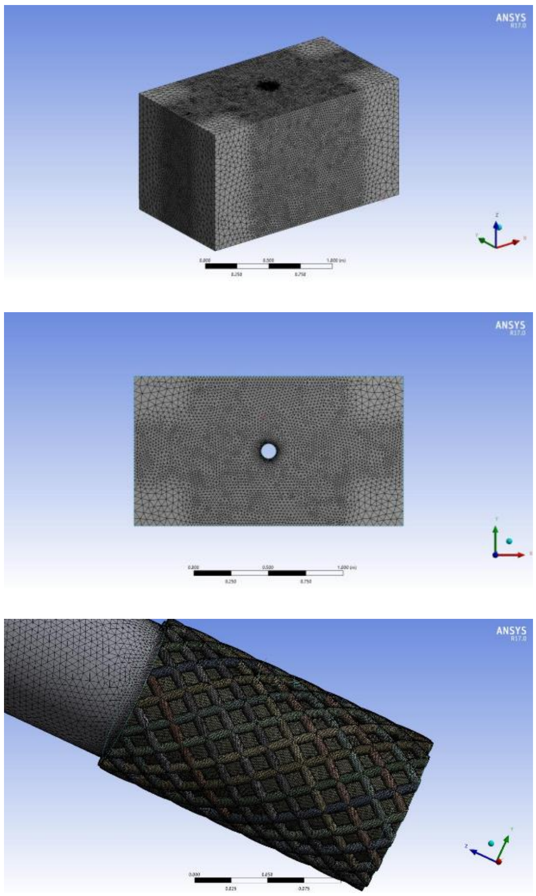
(b)

Fig.4 Numerical models of the monopile foundation. (a) Before using Fishnet (b) After using Fishnet.

Then the fluid domain and the monopile numerical models in Fig.4 are discretised by using the settings listed in Table 1. Here, it is worth noting that the meshing results obtained before and after using the 'Fishnet' technique will be different. Moreover, the modification of the size of fishnets and the diameter of fishnet thread can also lead to the change of meshing results. Due to the difficulty of presenting the meshing results obtained in all scenarios, herein only the meshing results obtained when the fishnet size is 0.01 m and the diameter of fishnet thread is 0.005 m are shown in Fig.5 as an example for illustration purpose.

Table 1. Settings in ANSYS FLUENT for meshing the domain of interest.

Parameter	Setting
Size function	Curvature
Initial size seed	Active assembly
Smoothing	Medium
Transition	Slow
Span angle centre	Fine
Curvature normal angle	12°
Min size	0.001 m
Max face size	0.05 m
Max tet size	0.05 m
Growth rate	Default (1.20)
Use automatic inflation	Program controlled
Inflation option	First aspect ratio
Fir Aspect ratio	5
Maximum layers	5
Triangle surface mesher	Program controlled
Topology checking	Yes
Pinch tolerance	Default (4.5e-3 m)



(a)

(b)

(c)

Fig.5 An example of meshing results. (a) Isometric view, (b) Top view, (c) Local meshes around fishnets.

4 Numerical calculation and discussion

Since the work described in this paper is only a preliminary research of the proposed 'Fishnet' technique, its contribution to scour reduction is investigated by considering only a limited number of scenarios. They are listed in Table 2. Where, the size of fishnet is indicated by $\boldsymbol{l}$ and the diameter of fishnet thread is indicated by $\boldsymbol{d}$. They both are shown in Fig.6.

Table 2. Scenarios considered in the investigation.

Size of fishnet l	Diameter of fishnet thread d
Without fishnet	-----------
0.01 m	0.005 m
0.01 m	0.01 m
0.01 m	0.015 m

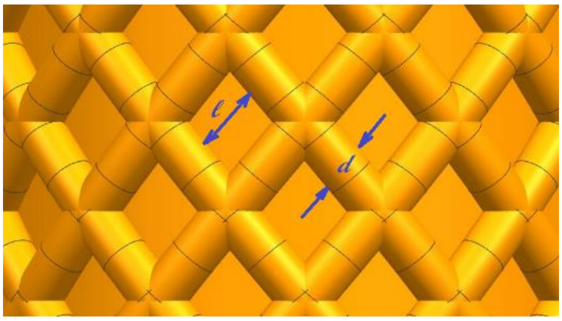


Fig.6 Numerial model of fishnets.

In order to demonstrate the working mechanism of the 'Fishnet' technique, the streamlines of the flow in the local area near fishnets are shown in Fig.7.

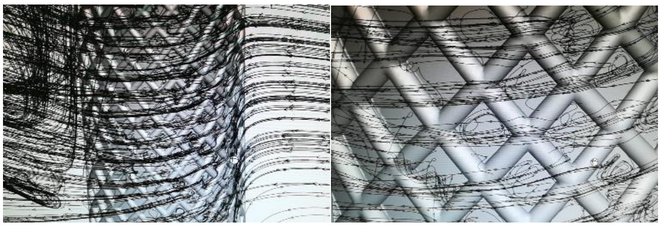
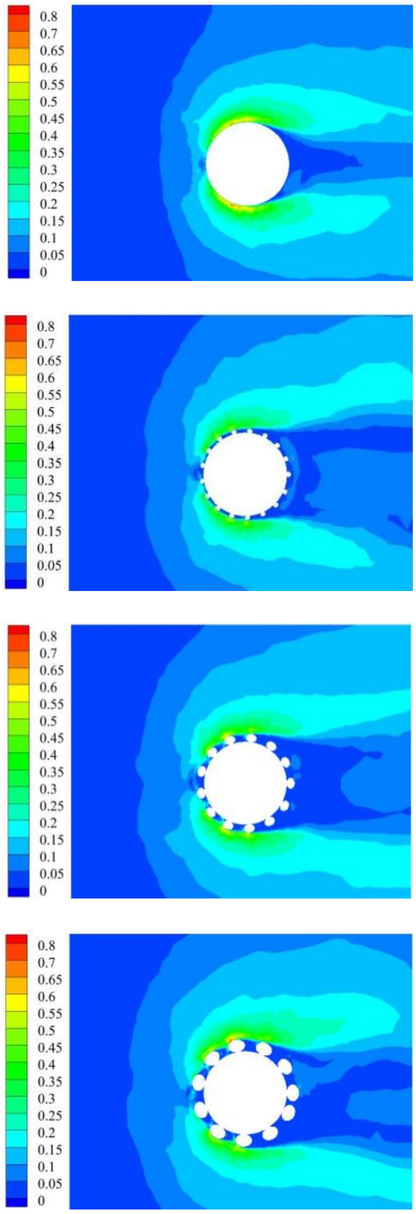


Fig.7 Streamlines in the local area near fishnets.

From Fig.7, it is seen that the down flow in front of the monopile foundation is disturbed when they meet fishnets. That will consume the energy of down flow and reduce their speed. This is beneficial to reduce the scour in front of the monopile foundation. Likewise, the intensities of the horseshoe vortices on the both sides of the monopile foundation and those behind the monopile foundation will be reduced by the fishnets in the same manner, although this phenomenon cannot be clearly illustrated here using streamlines. Therefore, based on the phenomenon shown in Fig.7, it is reasonable to believe that the application of the 'Fishnet' technique can effectively reduce the scour around the offshore wind turbine monopile foundation. However, it can be imagined that the different design of the 'Fishnet' technique will lead to different reduction amount of the scour. Therefore, the 'Fishnet' technique will be optimised subsequently.

In order to simplify the investigation, herein the size of the fishnets $\boldsymbol{l}$ is fixed at a constant value 0.03 m, the diameter of fishnet thread $\boldsymbol{d}$ is changed in different scenarios. In the following calculations, the value of $\boldsymbol{d}$ will vary in the range of 0.005 m to 0.015 m, as listed in Table 2. Since the effect of scour is closely related to the shear stress on the surface of seabed, i.e. the larger the shear stress, the more easily the hole can be created around the monopile foundation, the shear stress distributions on the surface of seabed that are obtained in different scenarios are shown in Fig.8.



(a)

(b)

(c)

(d)

Fig.8 Shear stress distributions on the surface of seabed. (a) without using fishnet, (b) $\boldsymbol{d = 0.005}$ m, (c) $\boldsymbol{d = 0.01}$ m, (d) $\boldsymbol{d = 0.015}$ m.

From Fig.8a, it is found that around the monopile foundation, there are four specific areas where the shear stresses are much larger than the shear stresses in other areas. Due to the presence of these large shear stresses, the erosion is most likely to happen first on the seabed in these four areas. Two of them are located on both sides of the monopile foundation, which are due to the horseshoe vortices there. The other two areas are located behind the monopile foundation. They are due to the vortices behind the monopile foundation. From Fig.8a, it is interestingly found that in comparison with the shear stresses caused by the vortices around the monopile foundation, the shear stress caused by the down flow in front of the monopile is much smaller in value. Based on this, it can be said that, in fact, the main driver of the scour is the vortices around the monopile foundation. Moreover, it can be predicted that the holes will appear first on the both sides of the circular foundation.

The comparison of Figs.8a, b, c and d has shown that after using the ‘Fishnet’ technique, the shear stress distribution on the surface of seabed does change somewhat. For example, it is found that in spite of the value of the maximum shear stress, the area of the region that shows large shear stress is reduced after using the ‘Fishnet’ technique. This indicates the positive contribution of the ‘Fishnet’ technique to scour reduction. But it is also noticed that the largest shear stresses are different in different scenarios, although they appear in the same position nearby the monopile foundation. This suggests that there must be an optimal design of the fishnets that can best reduce the scour. In order to identify the best design of the ‘Fishnet’ technique from the calculation results, the maximum shear stress obtained in all considered scenarios are plotted in Fig.9.

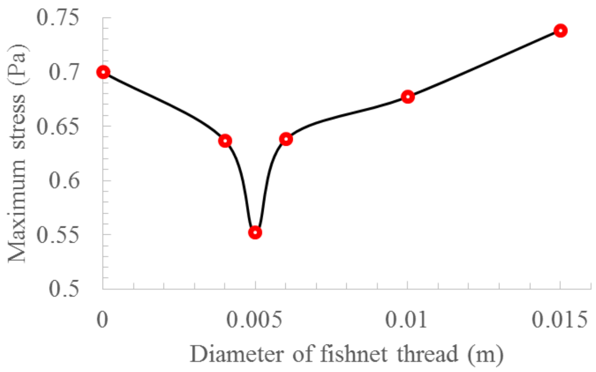


Fig.9 The maximum shear stress obtained in different scenarios.

From Fig.9, it is found that before using the ‘Fishnet’ technique, the maximum shear stress on the seabed is 0.69977 Pa. After the bottom section of the monopile foundation is covered with the fishnets of which the diameter of thread is $\boldsymbol{d = 0.005}$ m, the maximum shear stress on the surface of seabed drops down to 0.55195 Pa. However, since this the maximum shear stress on seabed changes to increase gradually with the increasing diameter of fishnet thread. For example, when the diameter of fishnet thread is $\boldsymbol{d = 0.01}$ m, the maximum shear stress is 0.67719 Pa, and when $\boldsymbol{d = 0.015}$ m the maximum shear stress reaches 0.73832 Pa. This seems suggest that $\boldsymbol{d = 0.005}$ m is the best design of the ‘Fishnet’ technique. However, this needs to be confirmed in the further research that will consider more thread diameter scenarios.

5 Conclusion

In order to explore a cost-effective and viable solution for reducing the scour around the monopile foundation of offshore wind turbines, a radical new scour reduction technique, namely ‘Fishnet’ is proposed in this paper. From the preliminary feasibility research described above, the following conclusions can be reached:

- The fishnets on the surface of wind turbine monopile foundation will disturb the path of flow when they pass through the foundation, which will consumes the energy of down flow in front and the vortices around the monopile foundation. This will be beneficial to the reduction of the scour;
- In comparison with the effect of the vortices, the seabed shear stress caused by the down flow in front of the monopile foundation is much smaller. So, it can be said that the main driver of scour is the vortices around the monopile foundation;
- After applying the ‘Fishnet’ technique to the monopile foundation, the area of the region that show large shear stress is reduced. But the maximum shear stress on the surface of seabed decreases at the beginning and then increases gradually with the increase of the diameter of fishnet thread. Therefore, it is sure that there must exist an optimal design of the ‘Fishnet’ technique. Based on the calculation results obtained in this paper, it is $\boldsymbol{d = 0.005}$ m when the size of fishnet is 0.03 m.

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